ROBOTS AND TELECHIRS:

Manipulators with Memory; Remote Manipulators; Machine Limbs for the Handicapped

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ELLIS HORWOOD LIMITED
Publishers · Chichester

Halsted Press: a division of
JOHN WILEY & SONS
New York · Brisbane · Chichester · Ontario

First published in 1983 by
ELLIS HORWOOD LIMITED
Market Cross House, Cooper Street, Chichester, West Sussex, PO19 1EB, England

The publisher's colophon is reproduced from James Gillison's drawing of the ancient Market Cross, Chichester.

Distributors:

Australia, New Zealand, South-east Asia:
Jacaranda-Wiley Ltd., Jacaranda Press,
JOHN WILEY & SONS INC.,
G.P.O. Box 859, Brisbane, Queensland 40001, Australia

Canada:
JOHN WILEY & SONS CANADA LIMITED
22 Worcester Road, Rexdale, Ontario, Canada.

Europe, Africa:
JOHN WILEY & SONS LIMITED
Baffins Lane, Chichester, West Sussex, England.

North and South America and the rest of the world:
Halsted Press: a division of
JOHN WILEY & SONS
605 Third Avenue, New York, N.Y. 10016, U.S.A.

British Library Cataloguing in Publication Data
Thring, M. W.
Robots and telechirs. – (Ellis Horwood series in engineering science)
1. Automation
I. Title
629.8'92 TJ211

Library of Congress Card No. 83-10685

ISBN 0-85312-274-1 (Ellis Horwood Ltd. – Library Edn.)
ISBN 0-85312-651-8 (Ellis Horwood Ltd. – Student Edn.)
ISBN 0-470-27465-4 (Halsted Press)

Typeset in Press Roman by Ellis Horwood Ltd.
Printed in Great Britain by Butler & Tanner, Frome, Somerset.

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CHAPTER 8

Telechiric machines

8.1 DEFINITIONS AND USES

The word telechirics was first proposed by J. W. Clark of Battelle ('Telechirics for operations in hostile environments', Battelle Report; see also his '*Ocean exploration by machine*', *Sea Frontiers*, 8, p. 76–83, May 1962). The word telechir means literally 'remote hands'. However, I shall take a more general definition as any system in which a man's brain controls mechanical hands to do complex manipulative tasks by means of signals provided by muscular contractions or nerve signals to muscles of his own body. This broad definition includes systems where a man uses mechanical hands or grippers close to his body to increase his strength, where a person who has lost the use of a hand controls a mechanical hand close to his body by signals such as movements of his eyes, sucking and blowing with his mouth and movements of his shoulder muscles. It also includes all the telechirs which are used remotely to enable a man to work in a hostile inaccessible region and it includes cybernetically operated micro-hands for work too fine for a man's hands. It does not, however, include the remote control of single-purpose machines such as a mole miner which has to be steered through the coal seam, by a human receiving sense impressions (although this device will be considered under the general section on mining in this chapter) nor does it include cranes or forklift trucks since these are purely single-purpose devices without the capability of complex manipulation such as rotation of the object about a horizontal axis.

Figure 8.1 is a diagram of all the feedforward controls and feedback information that are possible in a complete telechir for remote work in an environment requiring mobility. The human operator A sits in a chair at the master station and can use his hands either to move a joystick (J_1) to drive the telechir about in its environment, or other joysticks (J_2) for example to raise or lower the 'head and shoulders' assembly C by a vertical traverse device on the telechir, or he can place them in *control hands* D consisting sometimes of mittens, the fingers going into one slot and the thumb into the other sometimes of a pistol grip with trigger or split cylinder. These *control mittens or control hands*

servocontrol the 14 degrees of freedom of the telechir's two hands. Usually this is done by attaching the mittens to *control arms* E which exactly duplicate the slave arms (although not necessarily to the same scale) so that the 14 controls do not have to be unscrambled by computer. These control arms do not have to be duplicates of the human master's arms; for example, they do not have to have the ability to move the elbow round while the hand remains fixed in space

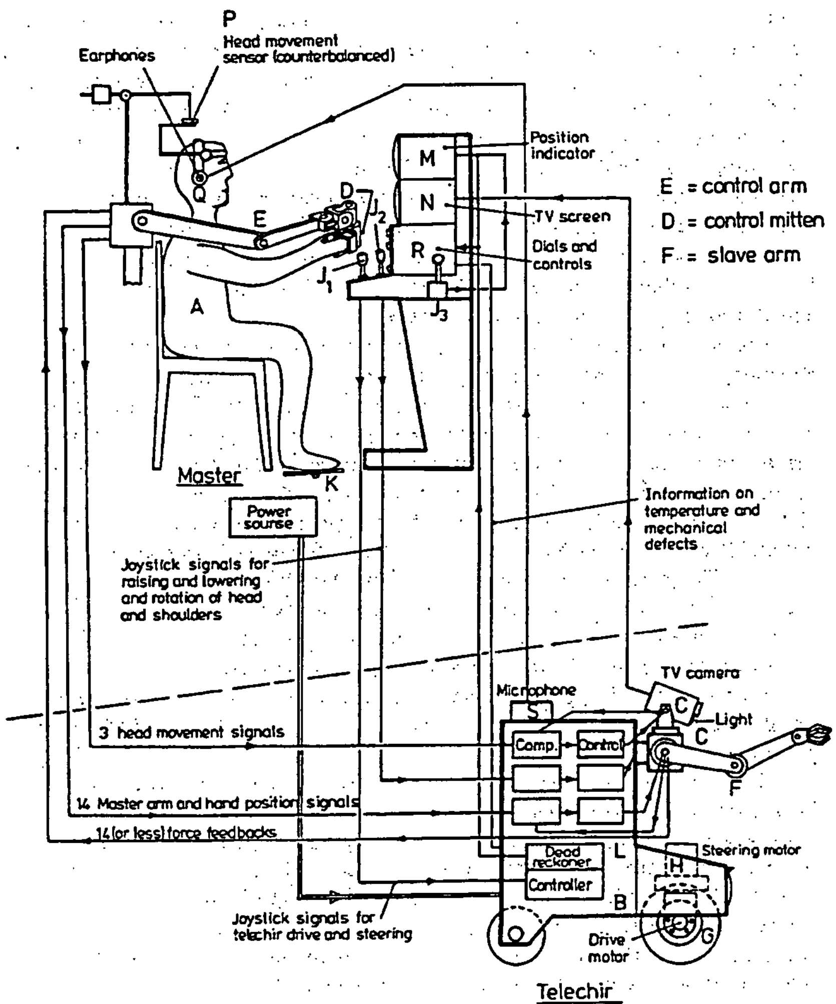


Fig. 8.1 – Diagram of components of a complete, freely mobile, telechiric system.

and orientation unless the telechir needs this freedom for access to different positions. They can thus have any type of movement that is convenient for the telechir in its environment so long as the human operator *can have vision and sensation as if his own hands were doing the job sufficiently so that he can use his trained hand-eye coordinated skill.* Various types of control arms that have been used for telechirs are shown in Fig. 8.2. When his hands are not in the mittens D, the control arms E and the telechirs arms F are in the closed position, unless the operator has locked them holding or carrying some object. He is then free to use his hands to work the joysticks. Movement of the telechir is shown diagrammatically as a system with two free wheels at the back and a wheel at the front driven by motor G which can be rotated by ± 180° from the straight forward position by steering motor H position. This is a drive system with the ability to go rapidly in any direction or spin round the midpoint of the back axle, but if the working environment of the telechir requires climbing over fallen stones or up a flight of stairs then any other walking system as described in Chapter 6 can be used; in space, rockets can be used, and under water, propellers. It is also possible to control the motors H and G by foot pedals K when the operator has his hands in the control mittens.

The dead reckoner L counts the turns of the drive motor G and knows the direction of movement of the body by means of a gyro compass and of the drive wheel by an angle indicator on the steering motor M. This information is used to indicate the position of the telechir on a screen M which carries a map of the working region in which the telechir can move. The operator can make fine corrections to this information by means of Joystick J3 when his vision system (TV cameras C and TV screen N) or his tactile information tells him that a noticeable position error has occurred as a result of cumulative inaccuracies.

The TV cameras C can be a pair to give binocular vision to the eyes of the operator A and a counterbalanced cap or helmet P can be used so that linear movement or rotation of the operator's head can be followed by the cameras C to give him 3-dimensional viewing. Alternatively he can learn to use 2 TV screens, side by side, receiving information from widely spaced cameras on B, and ultimately he will have genuine 3-dimensional vision provided by remote moving laser holography.

The control mechanical arms E moved by the operator's hands not only servocontrol the 14 movements of the telechirs arms and hands F but also receive a limited number of feedback force signals, say, two at the shoulder to enable the operator to sense the weight and inertia of the telechir arm, hand and object held. It can also provide one or more tactile signals to his hands, or these contact signals and others for contact of the telechir body can communicate with dials R or give an audible warning signal to the earphones Q. These earphones can also receive sounds from the microphone S.

The power source is shown as electric, transmitted by cable with the control and feedback wires from the operator's cabin, but provided the communication

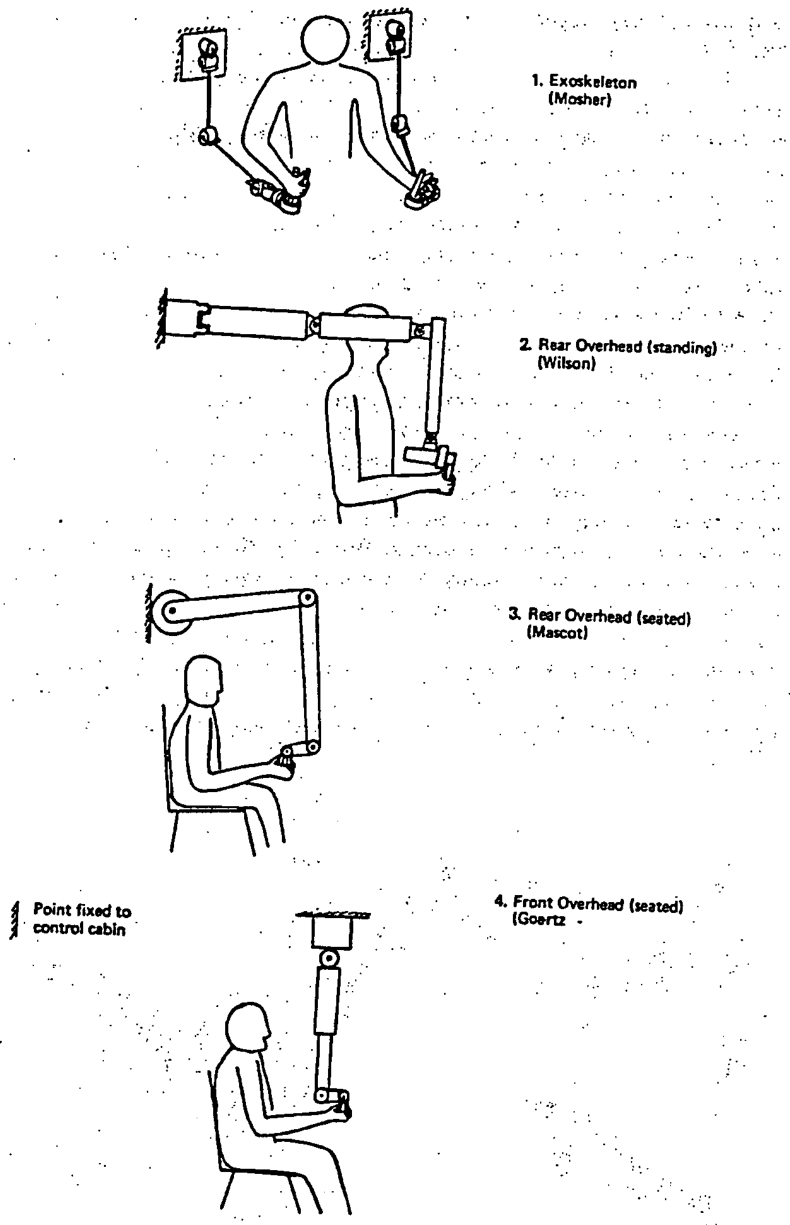


Fig. 8.2 – Various types of control arms used in telechiric systems.

is available it may be battery-operated or even a local prime mover with its own fuel tank.

The first work on telechiric machines was done in connection with the handling of radioactive materials which are known to have extremely harmful effects on the human body and from which the human body must be shielded, either by a considerable distance or by massive shielding. A great deal of work has also been done on telechirs in space, where it is much cheaper to put a non-air-breathing machine than a human being, although in this application there is the very severe handicap of the long time delay of the two-way radio communication. Active work is now beginning to enable people to do jobs deep in the sea without going down in diving suits or diving bells and work has just been started on the possibility of mining coal and other minerals by means of telechirs. This work will all be described later in this chapter but here we can speculate on how far it will be desirable to develop telechirs in the twenty-first century.

One of the present uses of rather elementary telechirs is bomb disposal where it is obviously far better to put a machine at risk than a human bomb-disposal expert. However, if we have not got rid of the need for the disposal of these devices for random civilan murder by the next century we shall probably have destroyed our whole civilisation in World War III and we need not pursue this line further. It will certainly be worthwhile developing undersea telechirs to the point where it is totally unnecessary for human divers ever to go down and we shall probably be able to operate an oil-drilling rig on the base of the sea with all the necessary work carried out by telechirs (see Fig. 8.3). Similarly there is no question at all that we shall have to develop mining systems whereby any mineral, but especially coal, can be won without men ever going down the pit.

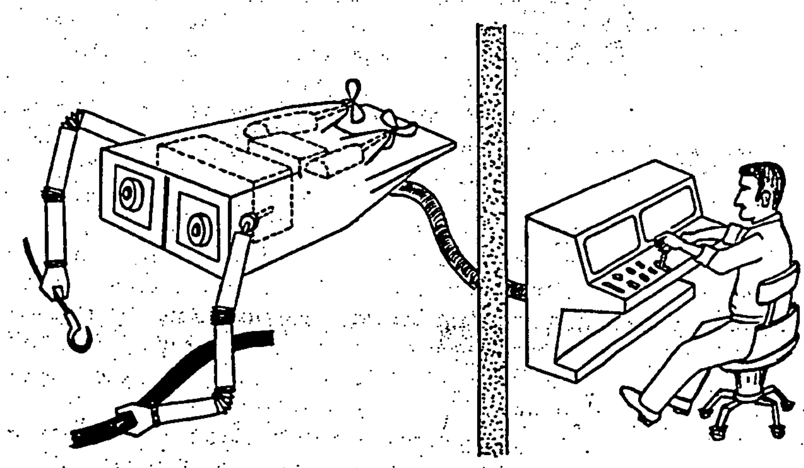


Fig. 8.3 – Diagram of underwater telechir.

This will give us the possibility of mining very thin seams without having to make roadways sufficient to carry men and without ventilating the mine. It also means that we can win coal far under the sea and at depths which are intolerable for men.

We shall still have certain tasks in factories which involve the risk of explosion or the escape of poisonous gases and there is no doubt that, once we have solved the problem of a relatively cheap telechir, all this kind of work can be done remotely from a comfortable and safe control cabin. Other ways in which the development of telechirs are likely to cause considerable improvements in human life are: (1) the use of a telechir for going into a burning building and rescuing people or extinguishing the fire chemically and safely from inside instead of playing hoses on it from a considerable distance; similarly (2) an empty building can be controlled at night for fire or other hazards with a single nightwatchman watching a television screen for the telechirs.

However, there will always be some jobs where the skill of a telechir cannot match the skill of the craftsman's hands handling the tools directly, quite apart from the fact that a telechir will always be slower than a human working directly with his hands. Examples are the craft skills of wood-carving or painting a picture, jobs requiring very fine sensory feel combined with close vision, such as fitting a small bolt into a nut or avoiding cross-threading a very fine thread, and jobs where it is necessary to handle materials with complex dynamic properties, such as folding a sheet or tying a shoelace.

Apart from remoteness there are other advantages in telechirs compared with the direct use of the human's arms and hands:

(1) Mechanical arms and hands can be scaled up by a large factor, both in length where arms up to 15 m long have been used and in strength where arms have been developed for lifting half a ton. The force feedback is correspondingly scaled down so that the operator feels as if he were handling a light object suitable for his strength; equally mechanical hands can be scaled down to perhaps one-tenth of the size of the human's hands associated with 10-fold visual magnification and an amplified force feedback†. It is probably not possible to go much further than one-tenth because the increased magnification gives a very short depth of focus, and depth of focus is necessary for three-dimensional tasks.

(2) It is possible to give the telechir more than two pairs of hands and arms and the human controller can control these in turn, clamping one pair before he moves on to the next. This has been proposed for surgery where one pair of hands can act as accurate manually positioned clamps while another pair

†For micro operation, force feedback should probably be scaled up as the square of the length scale ratio to correspond to areas for forces such as cutting. On the other hand for arms n times larger than the human ones the forces should be scaled down as $1/n^3$ since the weight or mass handled is relevant.

works with forceps and scissors or needle. It has also been proposed (Fig. 8.4) (R. Goertz, 'Manipulator systems development at ANL', *Proc. 12th Conference on Remote Systems Technology*, Nov. 1964, p. 117) to use one pair of arms or even two pairs for climbing up scaffolding or holding on to an underwater structure while another pair of arms and hands carries out the work on the structure.

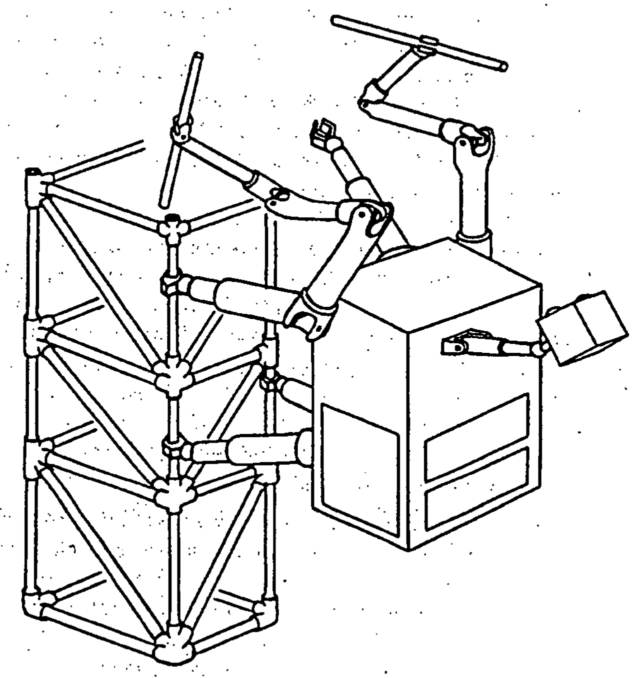


Fig. 8.4 – Telechir concept with six limbs.

(3) The most usual feedback system for telechirs is three-dimensional vision and force feedback to the human operator's muscles but it is also possible to give other forms of feedback in terms of signals on a second television screen or dial gauges so that considerably more information is available for the operator. There can also be audio feedback either of sounds in the machine area or of warning signals, triggered for example by tactile contact.

However, feedback is very expensive and the unilateral telechiric system with the feedforward signals only for the arm and hand is very much cheaper but of course visual feedback is essential. Moreover, force feedback being much more

complex has much more to go wrong. There is no doubt that mass production of telechirs will bring down the cost of force feedback but it will also probably always be necessary to have only a certain limited amount of force feedback, the minimum probably being the inertial and gravity forces felt at the shoulder and some kind of touch sensitivity at the hand.

During the 30 years since the first work on telechirs, considerable progress has been made in increasing the skill of carrying out operations remotely; thus R. Goertz writing in November 1964 at the Proceedings of the 12th Conference on Remote System Technology after 15 years work on the development of general purpose manipulators for radioactivity says 'Although considerable progress has been made in the development of manipulators the rate of typical hot laboratory work with a high-performance electric or mechanical slave manipulator is only about one-eigth the speed of performing the same operation directly with the hands'. By the proceedings of the 21st conference in 1973, Vertut *et al.* (p. 38, 'Contribution to defining a dexterity factor for manipulators') defined the time efficiency factor as the ratio of the time needed to perform a certain task using a manipulator and the time to do it directly by hand. They studied two types of tasks:

(1) Grasping, load displacement and simple assembly operations.
(2) Turning valves and plugging electric cables.

They found time efficiencies for bilateral master/slave systems ranging from 1.3 to 4.5 while open systems with no force feedback had time efficiencies ranging from more than 100 to 10. For more complex operations the time efficiencies of even the bilateral manipulators range from 3 to 7 and the unilateral range from 30 upwards. In general they concluded that force feedback improves the time efficiency by a factor of 5 to 7 compared with the unilateral arm. In 1977 Wilt *et al*†. of General Electric studied tasks which would be too heavy to do by a man directly, in order to compare the *replica master* and *resolved motion rate control* systems with force ratio 24 and size ratio 6.2:1. The replica master has bilateral force feedback. This work showed the replica master to have a distinct improvement in time although this was not as great as with low gain manipulators. The bilateral control makes it easier to perform the tasks without errors, reduces the mental effort and requires a less skilled operator. The force feedback does cause physical fatigue but as he is only handling a small part of the real force this is much more than offset by the reduction in mental effort.

8.2 TELECHIRS TO INCREASE A MAN'S STRENGTH

Two types of telechirs have been developed whereby a man is close to the task and uses direct vision to operate hands with the strength of a crane and with

†D. R. Wilt, D. L. Pieper, A. S. Frank and G. G. Glenn, 'An evaluation of control modes in high gain manipulator systems', *Mech. and Machine Theory*, 1977, 12, p. 373.

force feedback. The first of these is the General Electric Hardiman (Fig. 8.5). This is an exoskeleton into which the man fits and it carries attachment to his body at the feet, forearms and waist. It is capable of load-handling tasks such as walking, lifting, climbing, and pushing with a lift capacity of three-quarters of a ton. The mechanical exoskeleton is controlled by the spatial correspondence to the movements of the limbs of the man inside it and he has a very much scaled-down force feedback so that he feels as if he is manipulating a comfortably light load. The machine is driven with a hydraulic servo system using oil at a pressure of 3,000 psi and the hydraulic bilateral system discussed in Chapter 4. A preliminary series of experiments was carried out at Cornell Aeronautical Laboratory to study the necessary movements of the joints so as to keep the

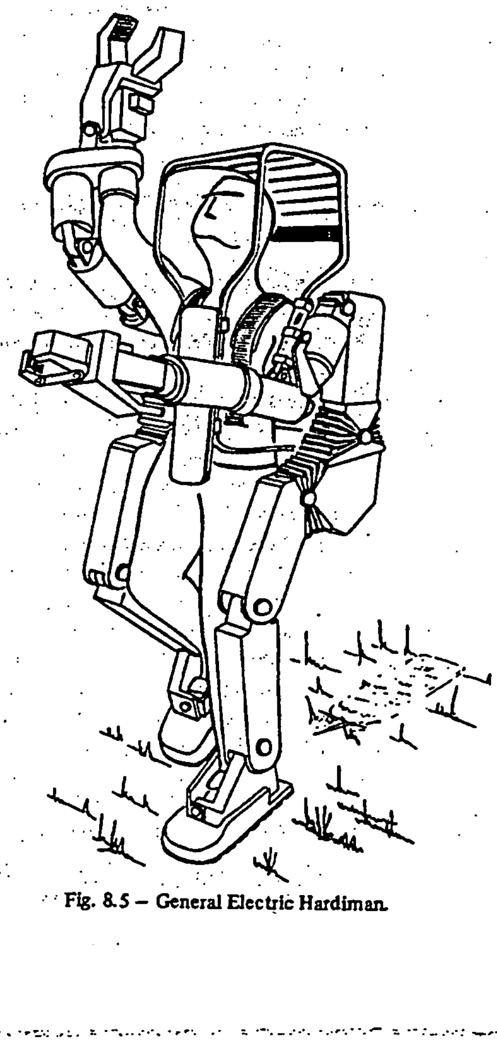


Fig. 8.5 – General Electric Hardiman.

number of joints to a minimum and to study the ranges of movements and the dynamic responses.

The second type of machine amplifier is a kind of combination of forklift truck and crane but with a gripper hand with force feedback to the human controller's hand in place of the hook or lifting prongs. An example is shown in Fig. 8.6 also from a General Electric publication of the 1960s where it is known as the Boom Handler. This uses the same principle of electro-hydraulic manipulation with bilateral force feedback. If developed fully a man could pick up a packing case weighing a ton with the same skill and sensitivity as if he were picking up a matchbox between finger and thumb. GE manufactures industrial manipulators ranging from 100 lb at 4 ft reach to 4000 lb at 24 ft reach (Wilt *et al., Mech. and Machine Theory,* 1977, 12, p. 374).

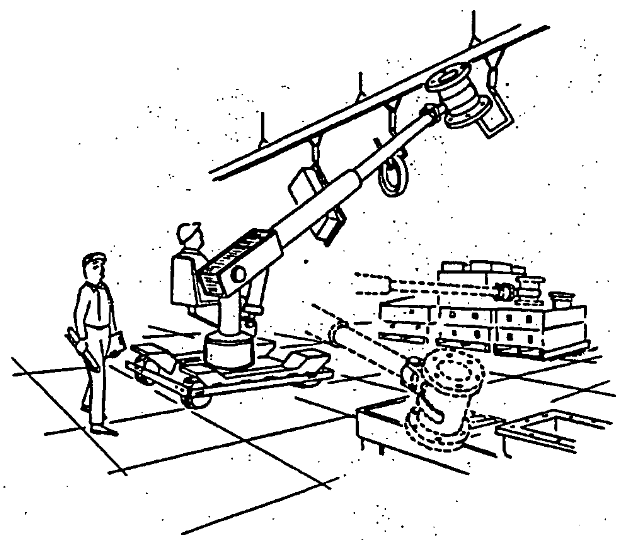


Fig. 8.6 – General Electric boom material handler.

8.3 TELECHIR DEVELOPMENT FOR HANDLING OF RADIOACTIVE MATERIALS

When work on radioactivity became essential and dangerous at the end of World War II, people started to develop mechanical master/slave manipulators whereby a human operator was linked mechanically from a master handle to a slave tong so that he could look through a thick protective window into a 'cave' and manipulate highly radioactive materials such as the elements of a nuclear

reactor pile. Figure 8.7 shows a sophisticated development of this type.† It is necessary to link the two systems through a hole in the protecting wall in the cave well out of alignment with the operator and all kinds of linkages have been provided, the most recent being based primarily on tension wires or tapes, with a pair being necessary for each motion. The problems of mechanical master/slave manipulators are the obvious ones of (1) looseness and play, (2) friction, (3) gravity forces which have to be neutralised with counterweights, (4) inertia of the arm itself and (5) limited volume of coverage. The force feedback is provided by the direct mechanical linkage but this is rendered very insensitive especially by friction.

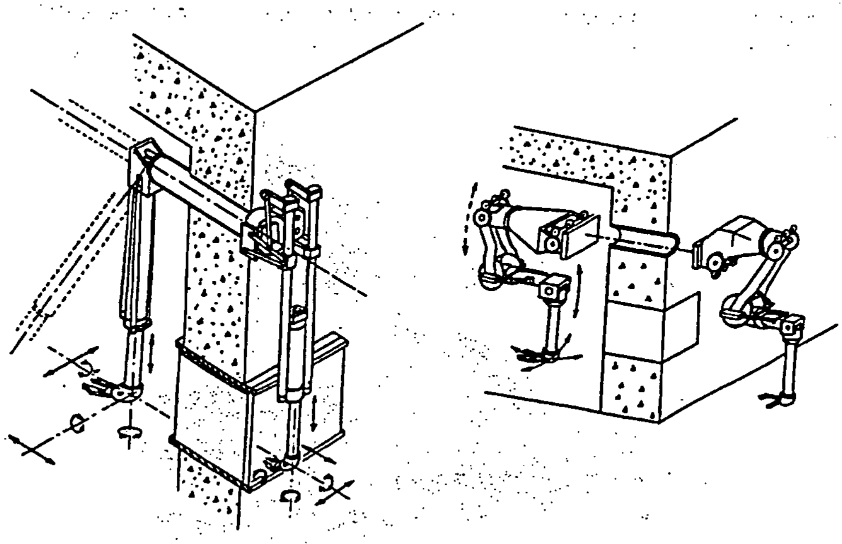


Fig. 8.7 – Mechanically linked telechirs.

In the 1950s and early 1960s the USA was planning to develop a nuclear-propelled rocket and also to develop an aircraft nuclear propulsion engine. The shield of this engine was between the nuclear system in the nose of the plane and the people behind. Hence when on the ground they could not be approached directly for repair and the General Electric Company with other groups, built a vehicle known as the 'Beetle' (*10th Hot Laboratory Proceedings ANS*, November 1962, p. 167). This vehicle weighed 85 tons and moved on tank treads to carry a man in a heavily shielded cab to drive it and operate these manipulators. He was shielded with 0.30 m of lead and five leaded windows 0.6 thick. It carried two power-manipulated telechiric manipulators and the cabin for the man and the

†'Manipulator systems development at ANL', R. Goertz, *Proc. 12th Conf. on Remote Systems Technology*, Nov. 1964, p. 117.

two manipulators could be raised on four telescopic hydraulic arms to some 25 ft above ground level. The motions of the manipulator arms are shown in Fig. 8.8. The device had a 550 hp main engine, an auxiliary power package and heavy duty batteries for short distance movement. When fully extended the arms had a reach of 5 m and could support a 40 kg load with a deflection of approximately 25 mm. There was no force feedback but direct viewing through the windows and by means of a periscope.

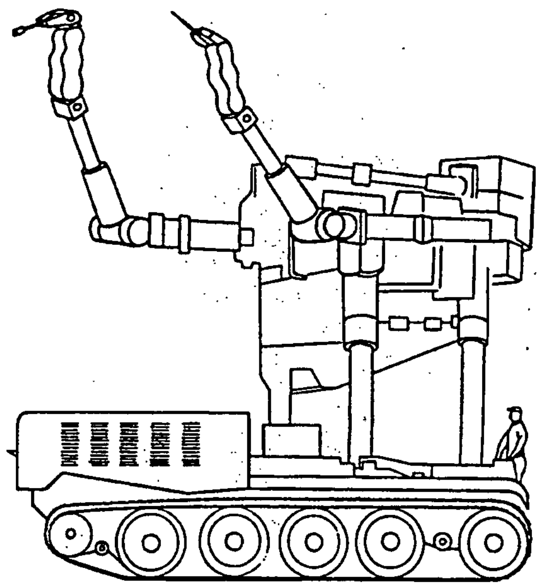


Fig. 8.8 – The 'Beetle'.

Very much more work has been done on the development of master/slave electric and hydraulic manipulators for work in radioactive situations than for other applications. These may be regarded as a development of the mechanical hands used in caves and indeed the first series of prototypes, that associated with Ray Goertz, operated the slave arm and hands by means of tension cables or tapes; but instead of these cables being directly connected to the master arm to transmit its movements they are operated by electric motors driven by servo systems with position comparison from the master arm. The communication was electric signals, which in all the early versions were analogue signals, although work is now starting on digital communication. By 1966 he had reached the Mark E4A ('ANL Mark E4A electric master/slave manipulator', R. Goertz, J. Grimson, C. Potts, D. Mingesz and F. Forster, *Proceedings 14th Conference on Remote Systems Technology,* 1966, p. 115). Each of the seven independent

motions of the manipulator was driven by a separate force-reflecting servo and the operator could feel all the load of the slave or half or one-fifth of it. The master arm had a maximum load of 4½ kg and the slave arm of 23 kg in any direction. Figure 8.9 is an outline drawing of the pair (a) slave arms and (b) master arms. Figure 8.10 shows the way in which the seven motors are operated by cables from drums driven by servo masters with about 40 to 1 gear ratio. One motor on each drive unit has an a.c. tachometer and another motor has a geared synchro to provide position signal data. The master and servo drive units

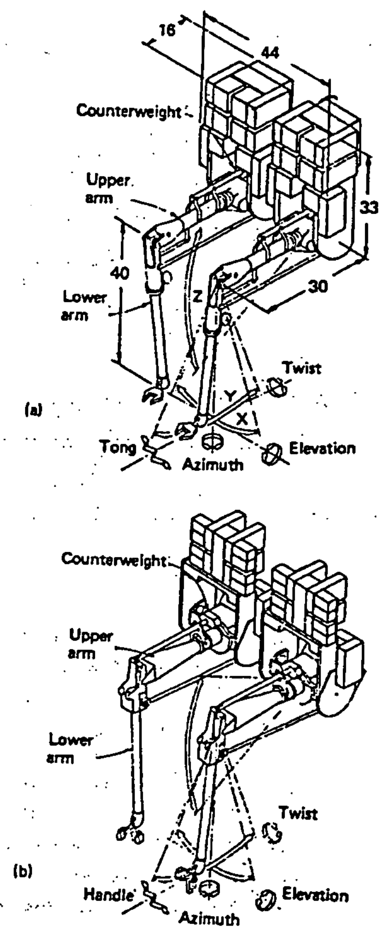


Fig. 8.9 – Outline drawings of (a) a pair of slave arms; (b) a pair of master arms.

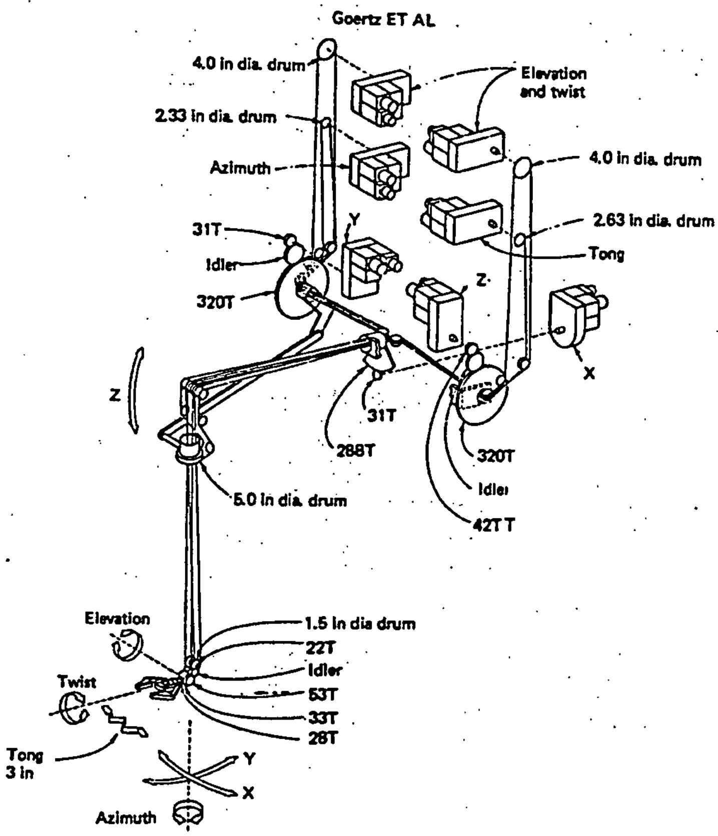


Fig. 8.10 – Servo motor drive system for manipulator of Fig. 8.9.

are connected to each other to provide force reflection but there is a built-in force ratio selector. The servo block diagram of this bilateral system is shown in Fig. 8.11.

Several other lines of work have followed this direction pioneered by Goertz. In 1966 at the 17th Conference on Remote Systems Technology (p. 154, 'Compact servo master/slave manipulator with optimized communication links') C. R. Flatau described a compact servo manipulator in which d.c. servo motors and other servo components were placed within the manipulator arms. He developed a variable force ratio feedback which varied the forces reflected at the master from 1:1 at low force to 3:1 at maximum force. Force reflection is gained by having bilateral symmetry between slave and master as shown in

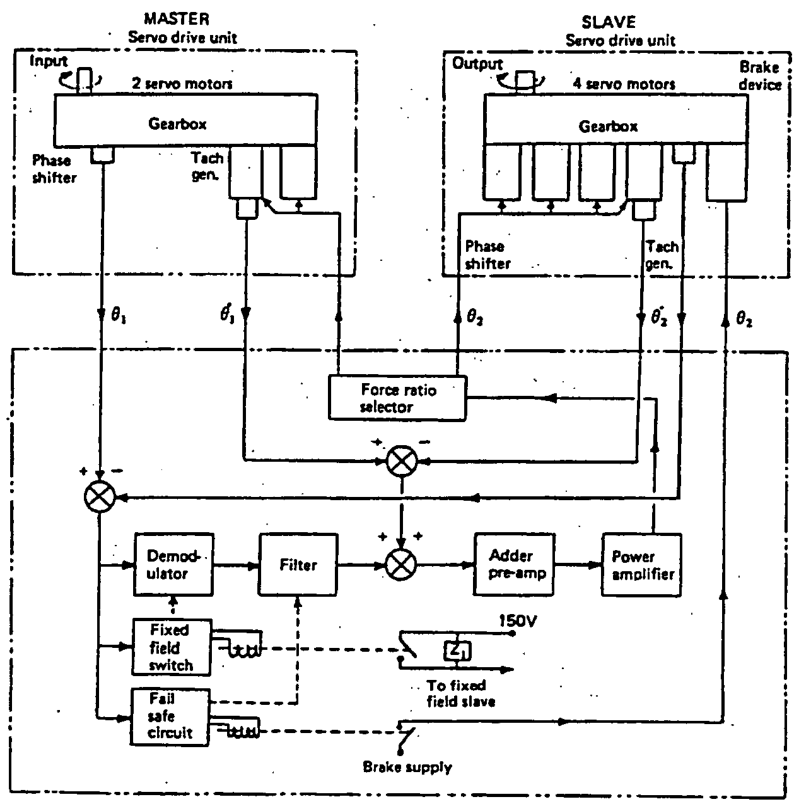


Fig. 8.11 – Block diagram of control system for Fig. 8.9.

Fig. 8.12. By 1977 at the 25th Conference (p. 169, 'A new compact servo master slave manipulator') Flateau has returned to a counterbalanced assembly in which the motors and gear reduction units are placed as counterbalances on the shoulder and the drive is by means of cables. Flatau's work has also been carried on in conjunction with the French Atomic Energy Commission, particularly Jean Vertut, and has led to the Virgule remotely operated vehicle which runs on three wheels and has two arms (Fig. 8.13) (*Proc. 25th Conference on Remote Systems Technology*, 1976, p. 175, 'The MA23 bilateral servomanipulator system', J. Vertut and P. Marchal, G. Debric, M. Petit, D. Francois and P. Coiffet.) These are also based on the use of tape and cable transmission with four of the motor actuators placed in the counterweight mass to give exact balancing, the other three motors are in a fixed assembly which drives the shoulder and elbow motions. The system operates on low inertia d.c. servo motors driven by an amplifier driver system by position control. The system of these arms is now

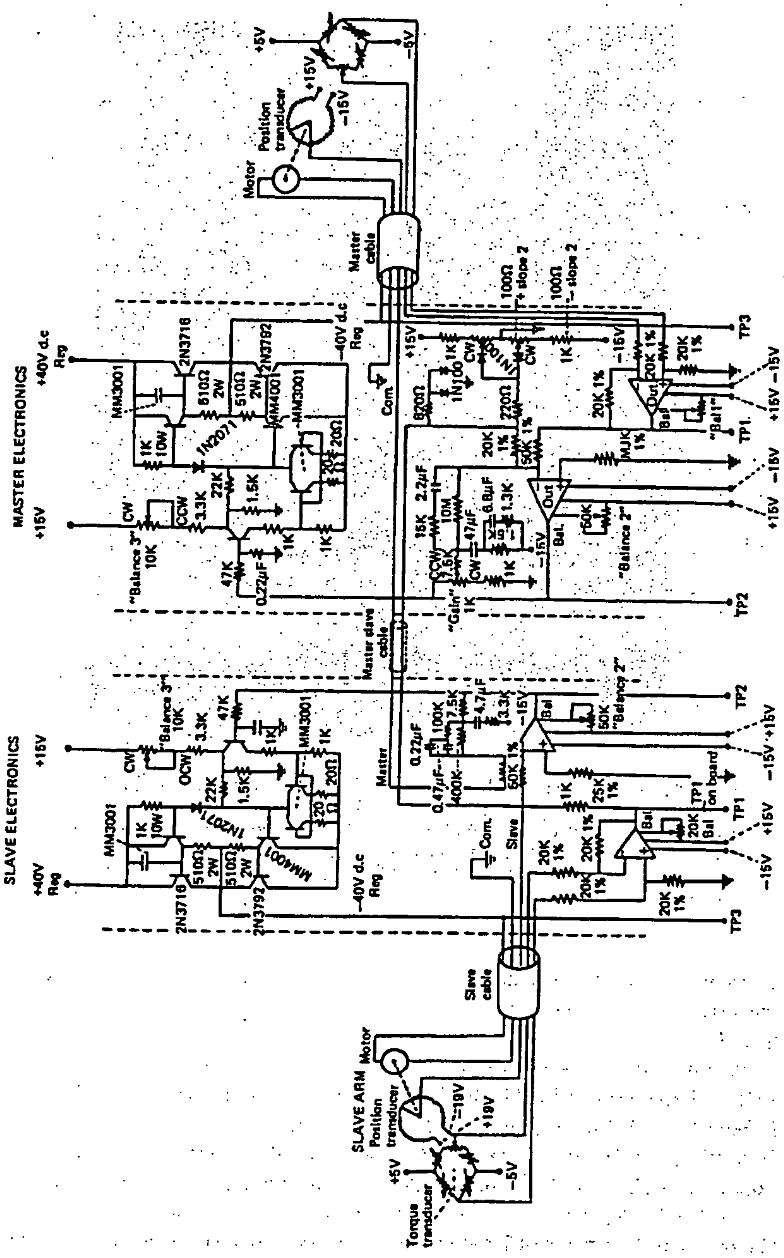


Fig. 8.12 – Bilateral telechir system with force reflection.

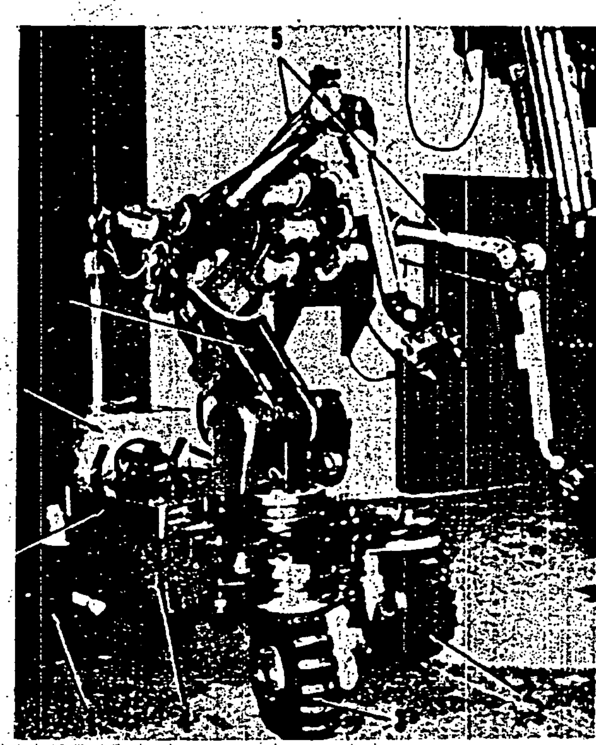


Fig. 8.13 – The Virgule tele-operator. (1) Four self-contained propulsion and steering wheels with special tread-pattern for stair-climbing. (2) Extended front wheel (both extended give stability). (3) Retracted front wheel (both retracted allow passage through a narrow door). (4) Batteries. (5) Pair of MA 22. (6) Three-degree-of-freedom-articulated support. (7) Right-arm power amplifier. (8) Multiplex communication.

commercially available with bilateral symmetry giving the force feedback and the system has also been applied in a deep submergence tele-operator which will be described in section 8.5.

Another line of work stemming from the work of Ray Goertz has been the Italian Mascot system Fig. 8.14 ('An electronically controlled servo manipulator', S. Barabaschi, S. Cammarata, C. Mancini, A. Pulacci and F. Roncaglia, *Proc. 12th Conference on Remote Systems Technology*, p. 143). This has a three-wheeled trolley, electric hydraulic control, a servo TV camera, with three-dimensional rotation and 7 degrees of freedom, all of which are operated by cables from servo motors on the body, except that the hanging elbow joints are operated by rods with parallel motion linkage. The body can be raised hydraulically from the base and

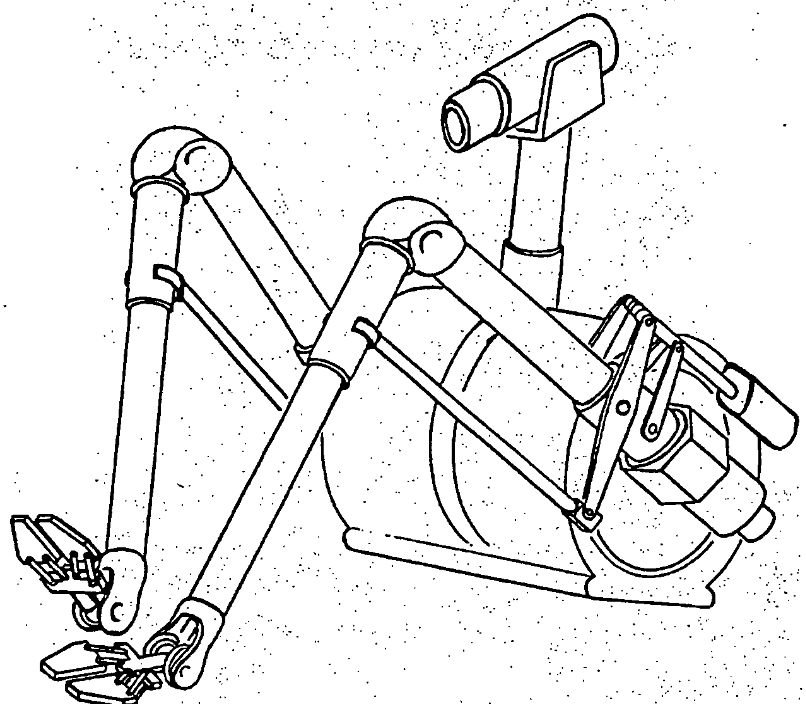


Fig. 8.14 – The Mascot telechir.

the shoulders lifted up so that the hands can operate up to a considerable height. This machine has also been developed for commercial manufacture and in the *23rd Conference on Remote Systems Technology*, 1975 (p. 247), its use on an overhead carriage with two-dimensional movements to cover a large area for a CERN 26-GeV proton syncroton was discussed (R. A. Horne and M. Ellefsplass, 'Long-range, high-speed remote handling at the CERN 26-Gev Proton Synchroton'). There is a bilateral force feedback but only two-dimensional vision from the television cameras; two of them are on articulating arms (Fig. 8.15).

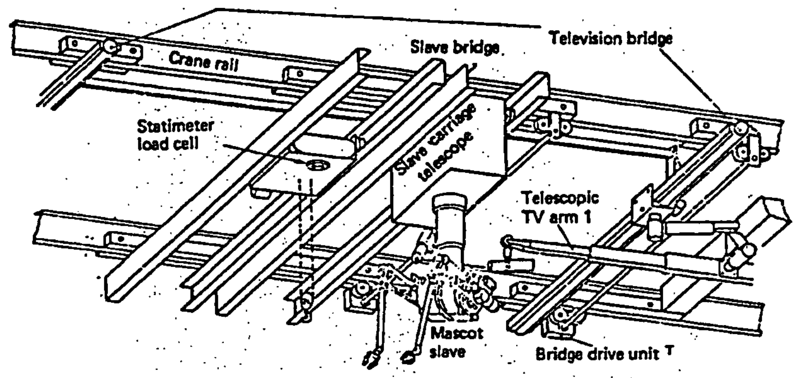


Fig. 8.15 – The Mascot telechir on an overhead carriage.

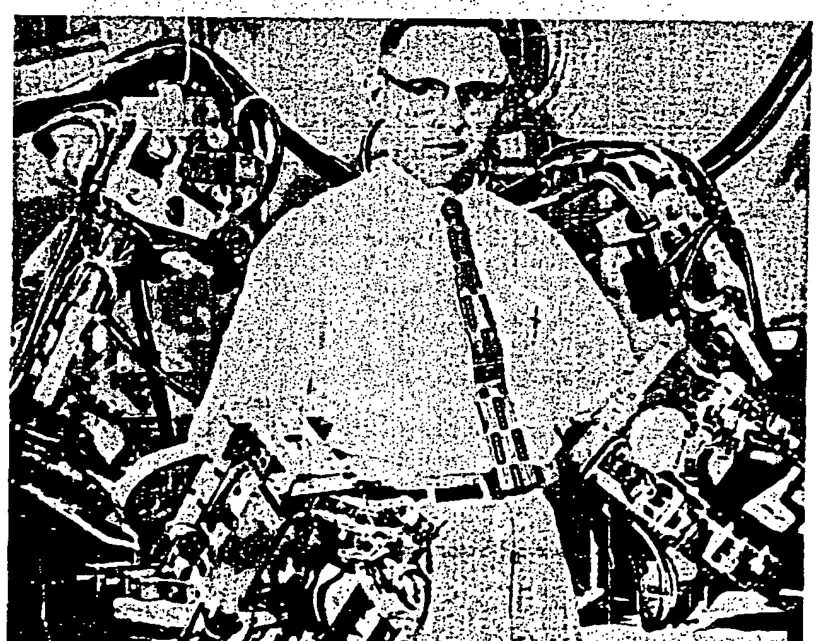


Fig. 8.16(a) – The Handiman servo manipulator: Master station.

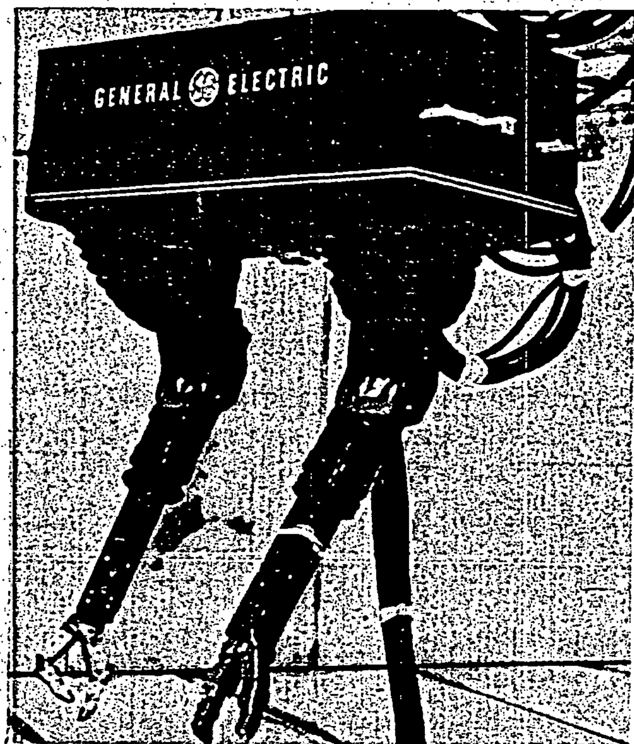


Fig. 8.16(b) – The Handiman servo manipulator: Slave station.

The other main line of work on radioactive handling is the unit based on hydraulic bilateral symmetry. This work largely started from the Handiman developed by R. S. Mosher of General Electric. Figure 8.16 shows the master and slave stations ('An electro hydraulic bilateral servo manipulator', R. S. Mosher, *General Electric Report;* also *SAE,* Jan. 9, 1967). The master and slave only have to be connected electrically since each has its own hydraulic pump; the circuit is that described in section 5.4.2. Each slave arm is capable of lifting 34 kg in its weakest position, that is when it is supported from the other arm by the maximum distance of 2.8 m. There are 10 degrees of freedom for the hand/arm assembly. The slave to master force ratio can be varied from 10 to 1 down to zero, but it is usually kept at 3 to 1. It is claimed that the use of the hydraulic system enables large force output to be obtained with relatively slight friction, rapid speed of response and comparatively small tubes for the power. The compliance is 3½% of full stroke under maximum load.

A water hydraulic telechiric manipulator was described by K. B. Wilson (Fig. 8.17) ('Servo arm — a water hydraulic master/slave manipulator', *23rd Conference on Remote Systems Technology*, 1975, p. 233). This also has bilateral symmetry of the servo mechanisms and uses *terminal control* in which the movement of the master's hand operates an arm of quite different geometry to his arm but of the same geometry of the slave. It is possible to get friction so low that the force threshold is 115 g. They developed a special back-drivable servovalve with poppet and piston construction rather than conventional spools to make it more dirt tolerant and they developed a compact water pump to supply the 7.6 l/min water for each arm at 100 bar. The system uses a microcomputer and A/D conversion hardware for counterbalancing and can therefore be readily made to work on a computer program.

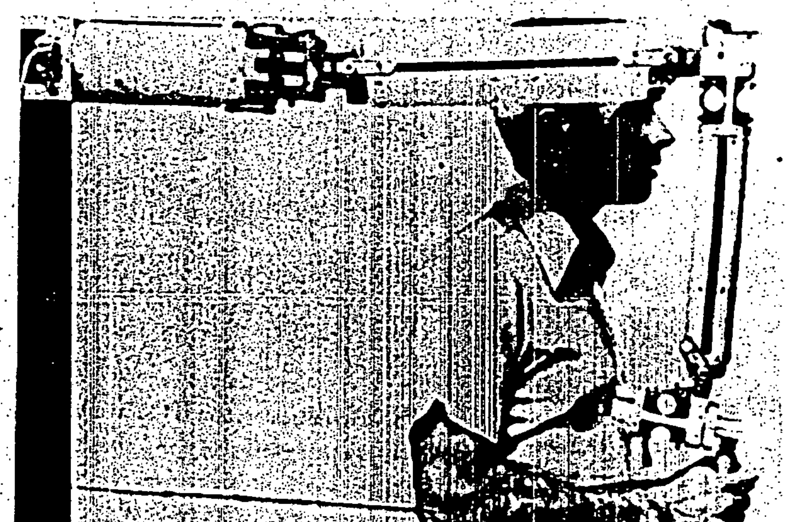


Fig. 8.17 – A water hydraulic telechir manipulator.

Unilateral manipulators have been developed in Germany and Britain and the Mobot in California. The very considerable need connected with the nuclear energy programme for handling these highly dangerous materials has clearly led to an immense amount of work and expenditure.

8.4 TELECHIRS FOR WORK IN SPACE

Much of the earlier work on telechirs for use in space was based on a control operator on the ground and this system suffers from the fundamental difficulty that the sensory message from the telechir to the human and the return signals

telling the telechir what to do can take many seconds or minutes at the great distances involved in space work, although it is only a fraction of a second for orbits close to the earth. A remotely controlled tug-based device intended for exchanging modules on orbiting spacecraft is described by F. C. Runge ('Space tug/spacecraft/module exchanger', *Mech. and Machine Theory*, 1977, 12, p. 451). This is to change modules held in a 5 x 5 block, when one of them breaks down or when it is required to change a scientific or working pay-load. It is particularly for communication and earth observation satellites, both for geosynchronous orbits and lower orbits. The manipulators are fairly simple as it is only necessary to select the appropriate module in the block, unlatch it and replace it with the correct new one once the block is latched on to the spacecraft. The servicing of communication satellites in geosynchronous orbit for design failures, random failures, and wear-out failures is also discussed by G. D. Gordon ('A user assessment of servicing in geostationary orbit', *Mech. and Machine Theory*, 1977, 12, p. 463).

A third type of orbital servicing module system where the modules are arranged in concentric circles and handled by a pivoting arm is discussed by G. W. Smith and W. L. D. Rocher ('Orbital servicing and remotely manned systems, *Mech. and Machine Theory*, 1977, 12, p. 65). M. H. Kaplan and A. A. Nadkarni ('Control and stability problems of remote orbital capture', *Mech. and Machine Theory*, 1977, 12, p. 57) discuss a proposal for a free-flying 'teleoperator' launched from a shuttle vehicle. The problem is to retrieve passive spinning and precessing satellites by means of giant fingers on an arm. The torque component on the fingers is absorbed by the grip of the fingers to produce a smaller spin motion of the combined system. The arm and hand are spun to match the expected satellite movement as it grips and there are countermasses which articulate to maintain dynamic balance.

In 1978 two papers in the *Proceedings of the 26th Conference on Remote Systems Technology* were concerned with manned remote work stations (MRWS) ('Manipulators for large-scaled construction in outer space', C. A. Nathan and C. R. Flatau; and 'Large scale manipulator for space shuttle payload handling', M. J. Taylor, p. 90).

The system described by Nathan and Flatau (Fig. 8.18) consists of a universal cabin to carry one man and the cabin is planned to have two sophisticated manipulator arms placed on a stabiliser arm with which it can grip hold of the work. The cabin is too small for the man to work full-sized controls and his arm controls are thus scaled down to one-third of the external arms. The drive and control is done with the system of electric motors with cables to the joints, and there are 7 degrees of freedom on each arm. This crew cabin with its three arms has windows for direct vision of the task being done although it can also have television cameras. It is 7.1 m in diameter with a 1 m degrees hatch, top and bottom and is 2.5 m high. This can be carried on a big arm from the shuttle or it could be free-flying or run on rails attached to the task. The ultimate aim

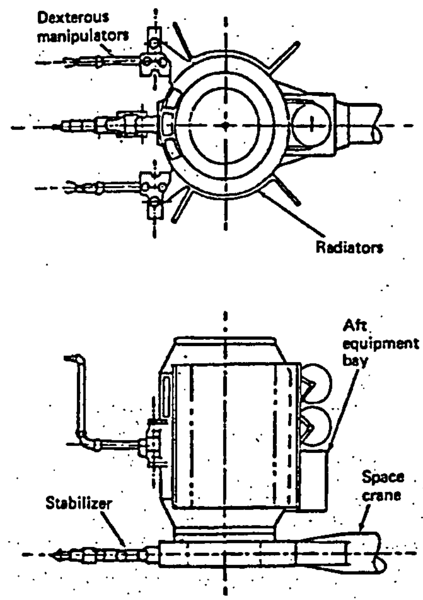


Fig. 8.18 – One-man space cabin with telechirs.

is that it should be possible to construct large structures in space from shuttles after 1990. Taylor (Fig. 8.19) discusses the shuttle remote manipulator system in which the manipulator arm is some 15 m long and is attached to the shuttle so that it can carry an end-effector capable of capturing a payload with quite large misalignment and also position payloads relative to orbiter axis with precision. The arm is controlled by a human operator on the shuttle who has direct vision from two windows looking aft into the shuttle cargo bay and also from two windows above him. He also has two television screens located adjacent to his control hand which receive signals from cameras located on the payload bulkheads and the wrist of the manipulator arm. There is no gravity problem in shuttle orbit and the arm can handle a 14.5 ton payload and give it a maximum speed of 0.06 m/sec. The operator controls the arm by means of two 3-degrees-of-freedom joysticks, the left-hand joystick provides the three transitional motions of the manipulator while the right-hand one gives the three rotational movements. The control system consists of one servo for each degree of freedom of the joints. Since the end-effector may have a very high or a very low inertia according to whether it is carrying the load or not, the gearing for motors on the drive is a combined low speed and high speed gear group. The low speed planetary gear gives 85% efficiency so that is adequately back-drivable to give force feedback.

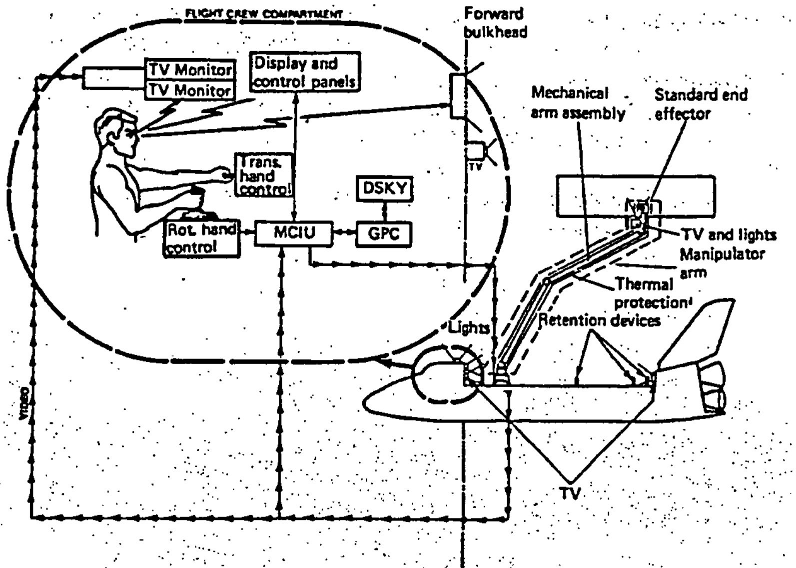


Fig. 8.19 – Shuttle telechir system.

8.5 UNDERSEA TELECHIRS

Three types of undersea telechiric manipulators have been extensively developed, particularly for naval purposes but also for commercial purposes such as surveying and maintenance of oil pipelines under the sea or of structural rigs for drilling. A third purpose for which undersea unmanned vehicles have been used is the scientific one of surveying the sea bottom in great detail, but these do not have telechiric slave arms.

(1) The first type is the small, manned, free-swimming submersible which may carry telechiric arms and have windows for direct vision. It may also have a lock system for loading a diver in and out. It must be powered with batteries or oxygen/fuel combustion and hence its work capacity and duration undersea are strictly limited.

(2) Towed submersibles with human operators inside. The operator usually looks through a window at the manipulator arms. American examples are the Alvin, Seacliff, Turtle and Scarab, and there is also the Dutch Bruker manipulator system attached to the Mermaid submersible. This is a hydraulically operated pair of arms controlled by an operator looking through a hemispherical glass window and each arm has 6 degrees of freedom with a hand with parallel grip.

(3) The unmanned systems operated by a cable from a ship. These include the American CURV (Fig. 8.20) and RUWS (Remote unmanned working system), the British Angus, the French ERIC and the Russian CRAB ('An overview of non-US underwater remotely manned manipulators', A. B. Rechnitzer, *Mech. and Machine Theory*, 1977, 12, p. 51) built for operation down to 4000 m with a 7 degrees of freedom telechiric manipulator. This is free-swimming but can also rest on the bottom of the sea. The latest version is the MANTA which causes the operator's chair to follow the pitch and role of the telechir to increase the operator's handling ability.

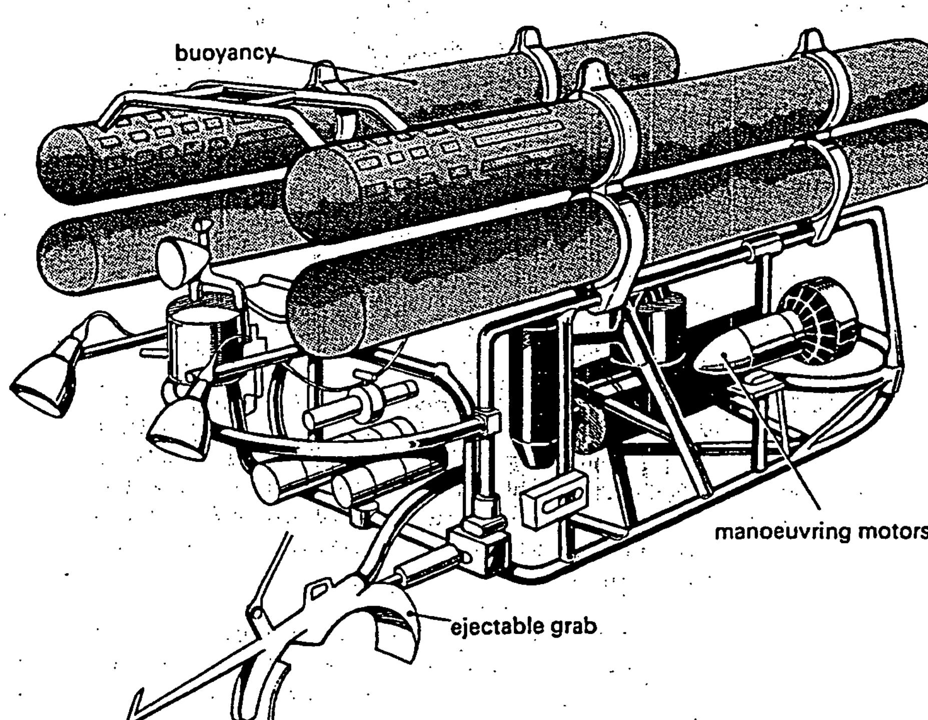


Fig. 8.20 – US CURV (1967) undersea telechir.

Under the first category of manned, free-swimming submersibles an example is the Vickers Pisces. This is battery-operated with lead acid batteries and has two men in it and two arms, one sophisticated manipulator arm and one torpedo recovery arm. The life support period is from 24 to 100 hours ('Mobility on the sea floor', *Engineering*, April 1974, p. 271). The big problem with such a machine

is to know exactly where it is. This is done by means of a scanning sonar and a transducer below the keel of the support ship. Pisces I recovered a tug sunk in 650 ft of water when it had been equipped with a hydraulic chain cutter on its manipulator which could cut through a 15 mm steel chain. More recently they have built a glass-reinforced, plastic submersible (*Offshore Engineer*, June 1977, p. 37). The Angus ('A Navigable General Purpose Under-water Surveyor', R. M. Dunbar and R. T. Holmes, *Electronics and Power*, 17 April 1975) is a small unmanned submersible tethered to a ship to give detailed information about the bottom of the sea. Electric power comes in a cable from the ship at 415 volts and propulsion is by means of a three-phase four-pole squirrel cage induction motor, voltage variation being used for speed control. The main cable is 18 mm multicore polyurethane sheathed with a breaking strength of one ton force. This carries three power conductors and 40 control and instrumentation conductors with one coaxial cable. Navigation is done by the long baseline acoustic technique with two transponder buoys on the sea bed. Information is sent back in the form of a closed circuit television and wide band hydrophone and there is also a 16 mm cine camera.

The US navy remote unmanned work system RUWS ('Position and force feedback give manipulator precise control, ease of operation', R. W. Uhrich and A. E. Munson, *Hydraulics and Pneumatics*, September 1973, p. 178) has a heavy duty claw with 4 degrees of freedom and a manipulator with 7 degrees of freedom weighing 28 kg and capable of lifting 20 kg at the maximum reach of 1.3 m. The whole system is hydraulically operated. The hydraulic system is so arranged that it works on ambient pressure plus 69 bar; the ambient pressure operates through that part of the 3 mm bore nylon pipes which are exposed to ambient pressure. They have developed a four-way pressure control servovalve and seven of these for the manipulator are mounted on a double-sided aluminium manifold head in an oil bath. The oil filled external tubing also carries the potentiometer cables but these are internal on the final arm. The six actuators of the arm and wrist are rotary vane and the parallel movement of the grip is driven by a cylinder, so the system is $\widehat{RR}$ $\overline{RRRR}$ P. The three wrist rotations operate on axes going through a point and have only unilateral control. The three arm movements are bilateral and the grasp is an open-ended control system giving a grip force proportional to the trigger depression against a spring.

The development of a system of manipulator arms and hydraulic tools which can be attached to this and other US Navy deep ocean manned systems for salvage operations is described in a paper by Estabrook *et al.* ('Development of deep ocean work system', N. Estabrook, H. Wheeler, D. Upler and D. Hackman, *Mech. and Machine Theory*, 1977, 12, p. 569). The Work Systems Package is a complete unit which has two grabber arms which can secure and hold on to a work piece for stability or assist the dextrous work arm. These are hydraulically actuated, have 6 degees of feeedom and a lift capacity of 114 kg at 2.74 m extension, with a grip force of 410 kg. The dextrous work manipulator is a 7

degrees of freedom hydraulic actuated rate controlled arm. The tubular aluminium holder which can carry a dozen tools is positioned opposite to the primary manipulator and just out of view of the frontal viewing area and bits such as drills and sockets for these tools can be held in clips at the edge of the tool holder. There is a high flow hydraulic system for powering tools as well as a low flow system for operating manipulators and the television cameras (pan and tilt) and a winch. Among the tools available are a chipping hammer with a rotary motor driving a cam against a compression spring, a low-speed rotary tool and piston-actuated cable cutter, spreader and jack.

SCARAB – The Submersible Craft Assisting Repair and Burial developed by MBA ('Design and application of remote manipulator systems', C. Witham, A. Fabert and A. L. Foote, *Proceedings 26th Conference on Remote Systems Technology*, 1978, p. 76) has been developed for undersea telephone cable repair and surveillance (Fig. 8.21). It can locate, unbury, attach, cut and return a cable down to 1830 m depth. It has an arm with 4 degrees of freedom (RRRP) plus a tool which it carries. They have concluded that variable rate control is

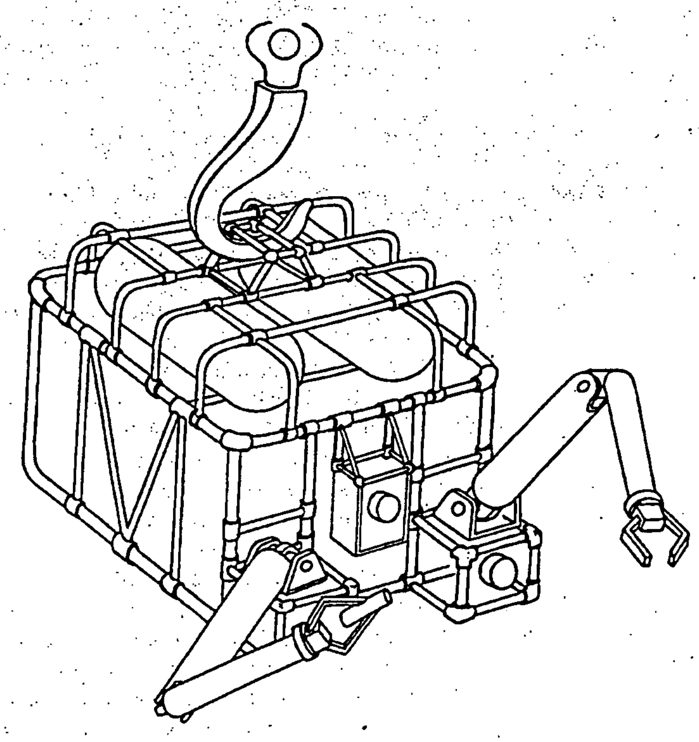


Fig. 8.21 – US SCARAB underwater telechir.

cheaper than position servo-control but is, of course, subject to drift so they use the latter to avoid drift. The actuators are hydraulically powered rotary vane and cylinder.

An unmanned manipulator submersible developed for the French Navy has been described in some detail by J. Charles and J. Vertut ('Cable controlled deep submergence teleoperator system', *Mech. and Machine Theory*, 1977, 12, p. 481). This is designed to search and investigage on the sea floor down to a depth of 6000 m. It consists of a 'fish-house' called PAGODE which acts as a lift between the bottom and the surface and carries the main cable and the 300 m tether cable for the neutral bouyancy teleoperator 'fish' which is called ERIC II (see Fig. 8.22). The combined system is dropped to the

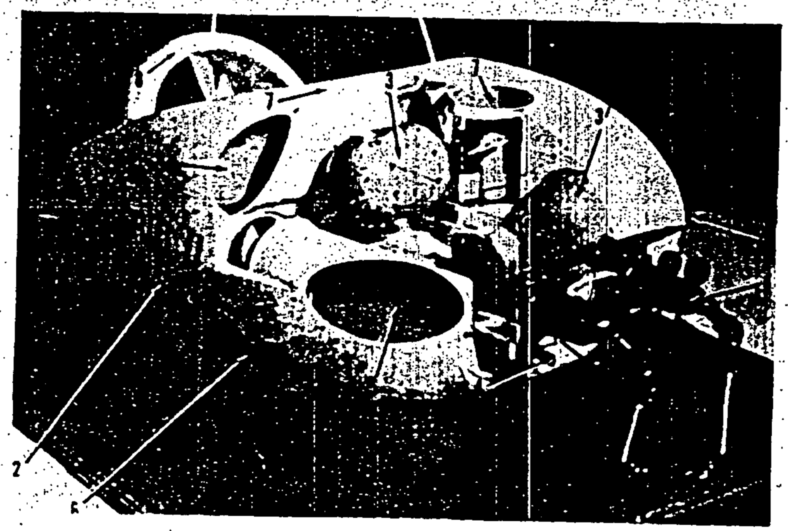


Fig. 8.22 – French ERIC underwater telechir.

required depth and then ERIC swims out of the 'fish house' to carry out the task. It is planned to have ultimately 6 degrees of freedom for the television camera, controlled by the rotation and movement of the operator's head in the support ship, the movements being in relation to his chair fixed in space. The telechir 'head' has binaural microphones connected to two earphones on the helmet in which the operator's head is placed (see Fig. 8.23). This helmet has binocular TV display and is counterweighted. ERIC weighs 4–5 tons and has 100 kW propulsive power supplied at 600 volts 400 Hz to keep the voltage control systems fairly constant and to transmit the required signals. The data transmission system is a composite one with analogue for specific purposes and digital for general purposes. The position of the 'fish'

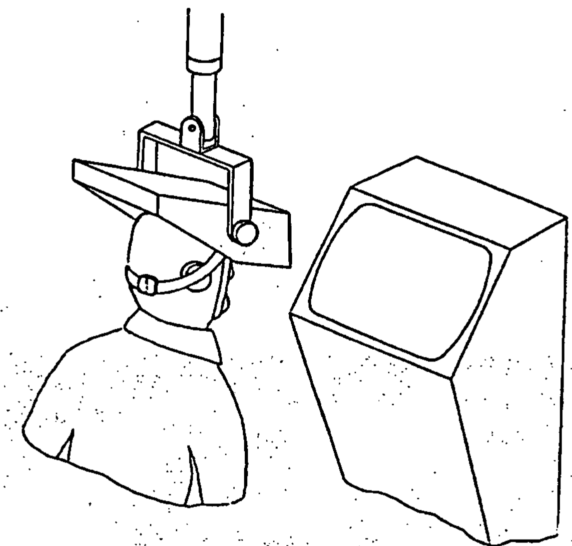
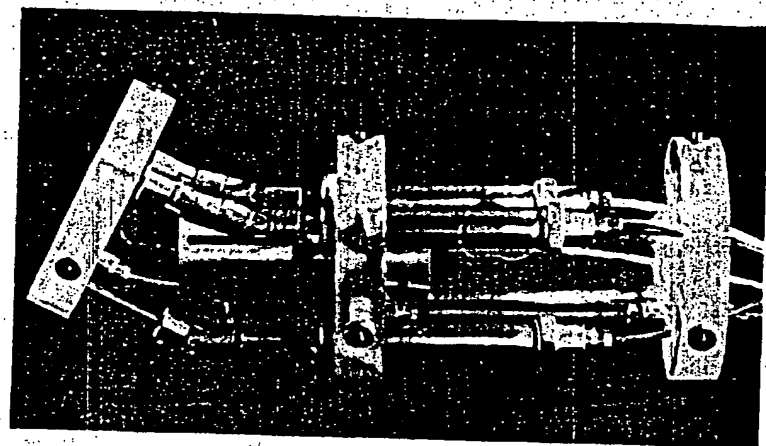


Fig. 8.23 – Head mobility system for ERIC telechir.

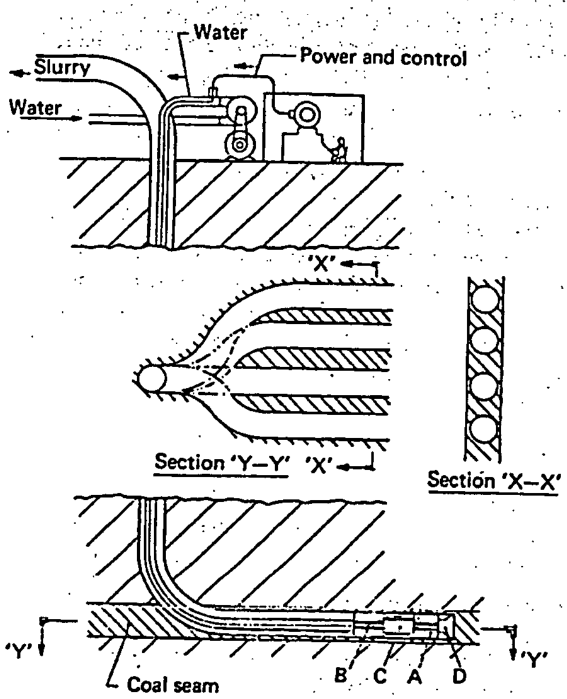
is determined over large areas by bottom acoustic transponders and panoramic sonar and locally by sonar and forward TV cameras. The basic intention is to mimic the overall capacity of a human diver without the limitations imposed by pressure. The system has a main propeller gimballed so that it always thrusts along the tiller tension direction with a tether so that it swims like a free body. It has three pairs of ducted propellers with variable blade angles and with thrust transducers for three-dimensional steering and trim. The two bilateral arms are worked by an electromechanical system with cable transmission for the movements.

8.6 TELECHIRIC MINING

The main cost of extracting solid minerals of all kinds from the ground is the cost of making holes in the ground in which human beings can work safely. With liquids or gases one has only to drill a hole of less than ½ m diameter and release or pump the fuel through the hole so these are much cheaper to win. With coal or other solid minerals on the other hand one has to make the mine safe for human beings to work in, have passages large enough for them to travel along, pump fresh air down and keep the content of methane in the atmosphere below the combustible limit; one has to pump water out and install lighting systems and man transport. Conditions of underground working are becoming less and less acceptable as human working standards rise and it is no longer possible to win coal from seams as thin as 0.5 m where a hundred years ago men



(a)



(b)

Fig. 8.24 – Steerable Mole Miner. (a) Model. (b) Diagram of operation.

used to lie on their side and break the coal out with a pick. If we can find a way of bringing coal to the surface without men going underground it can give the world a reasonable energy supply for at least one hundred years, including all the people in the under-developed countries. The author has been working on this problem for 20 years, his first proposal ('Mole mining', in Crookes and Thring, *Energy and Humanity*, Peter Peregrinus, p. 166) was a surface-controlled mole miner in which the coal crushed by the circular cutting head was pumped to the surface in a stream of water. This was similar to an oil well drill except that the mole could be steered round a corner and steered in the seam of coal by having sensing devices in the cutter at the four corners, so that it could tell when it reached harder rock outside and the human on the surface could then steer it. Figure 8.24 shows a model and a diagram of operation. The cutting force was produced by dividing the body at the front of the flexible support tube in to two parts, first the rear part was jammed into the hole by three feet (each 120° of the cylinder) that were forced radially outward while the cutting head on the front part was forced forward by three or four arms which could be worked differentially to provide the steering. When it reached the end of the stroke the radial feet on the rear part were released and the radial feet on the front part were forced out so that by reversing the stroke of the three main rams the rear part and the flexible tubes could be drawn up behind it. The main problems with this machine would be (1) the friction of the tubes dragged behind it and (2) supporting the bore hole so that the machine could be withdrawn when it reached the end of the cut.

Another scheme which has been proposed is to have a mole which seals itself in the hole it burns through the coal seam so that when it is fed with air at one atmosphere and it compresses this to 5 or 10 atmospheres it can throw a high pressure jet of air at the coal in front. The burnt gases pass through a turbine on the machine which drives the compressor and and electric generator and the electricity and cooled combustion gases are brought to the surface. The problems in developing this machine are:

(1) sealing the machine in the seam as it slowly advances with a pressure difference of many atmospheres;
(2) dealing with ash from combustion and shale in the seam;
(3) it requires fully developed telechirs as men could not go down the pit for repairs, maintenance or changing the region being burnt once it had been lit.

Considerable experiments have gone on underground gasification ('The underground gasification of coal' *National Coal Board. Pitman*, 1964; reappraisal 1976). But it has been shown by calculation that it is extremely difficult to do more than drive off the volatiles leaving the coke behind; the gas has a very low calorific value (less than one tenth that of natural gas) unless pure oxygen is used for combustion and it is difficult to pierce another hole for further gasification after one hole is exhausted as this requires sending men down into a

burning pit. In any case coal has far too many uses on the surface to confine it to a gas which is only fit for burning for power at the pit head, indeed underground gasification was only considered in Britain for coal near the surface but uneconomic for mining conventionally. However, it may be possible to develop a method of underground distillation or steam extraction for the tar in the enormous tar sand deposits of Athabaska (Alberta, N. Canada), preferably using telechirs.

In the process of pipe jacking concrete cylinders are thrust hydraulically into a horizontal hole in the ground while one man at the front end of the hole excavates the ground material so that the hooded shield at the front can be pushed forward while another man barrows the spoil back to the entry pit. This is clearly an ideal application for telechirics since the adaptability of the man excavating to varying soil conditions (e.g. finding large boulders in clay) is an essential prerequisite of the operation.

In 1970 the author proposed true Telechiric Mining (see Fig. 8.25) ('Mining without men going underground', M. W. Thring, 1980 *ASME*, 81-Pet-21) which

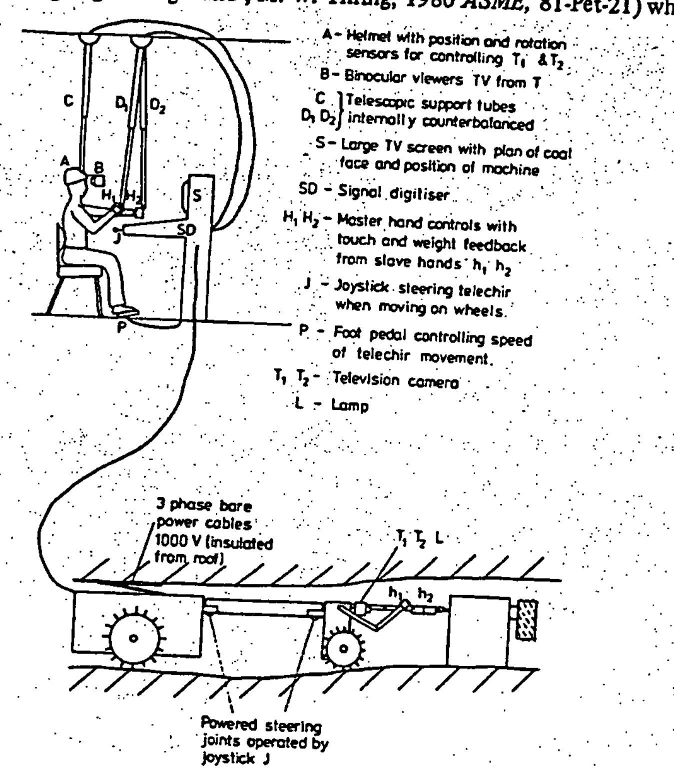


Fig. 8.25 – Diagram of telechiric mining.

may be defined as a system in which the underground machinery for cutting roadways, cutting the coal, transporting it, and for maintaining the conditions in the pit, are all essentially similar to those which are at present operated by men down a modern well-automated pit, but the men stay on the surface *never going underground* and do the tasks that they would at present do underground by means of mobile telechirs communicating with their hands, arms and eyes, combined with extra sensing devices on machines such as coal cutters. These telechirs may be independent, mobile machines, equivalent to the head and shoulders and arms of a man attached to a body which can move at a brisk speed in a space in which the man can only crawl on hands and knees. Figure 8.26 shows a series of models of possible telechirs for mining. Alternatively they may be attached as arms and eyes on a machine so that a man on the

Fig. 8.26 – Models of mine telechirs.

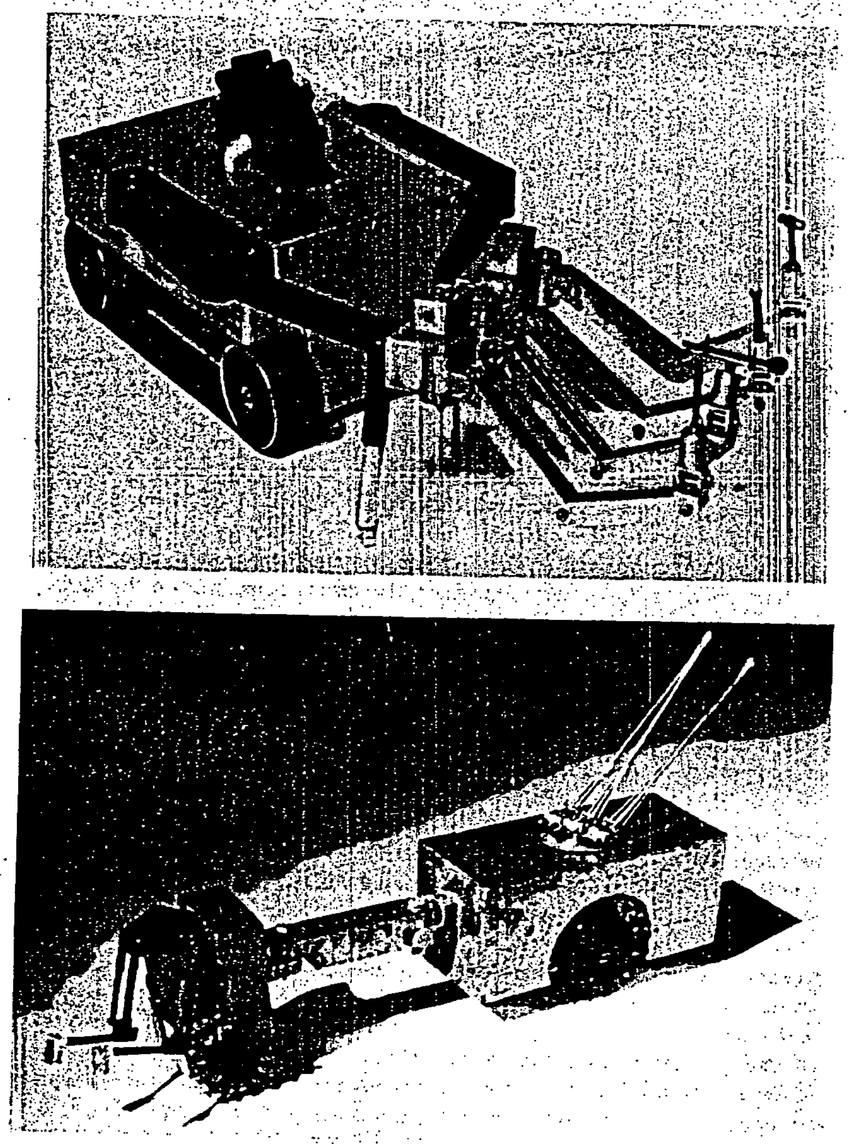


Fig. 8.26 – Models of mine telechirs.

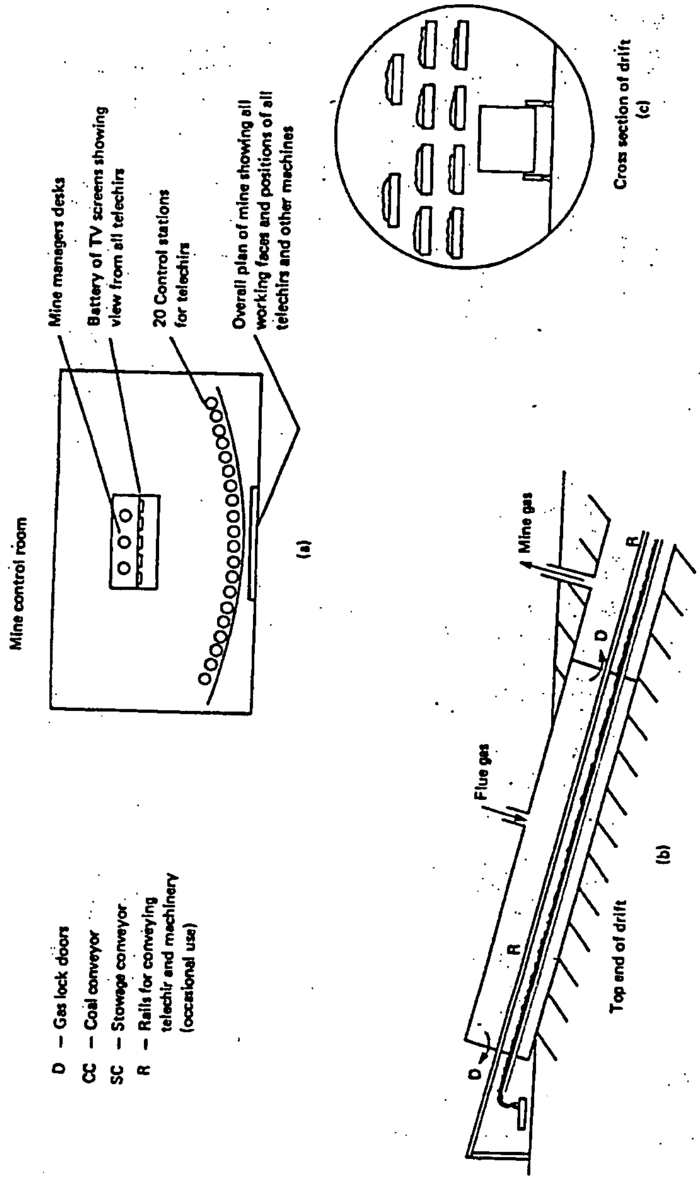


Fig. 8.27 – Possible telechiric mine layout.

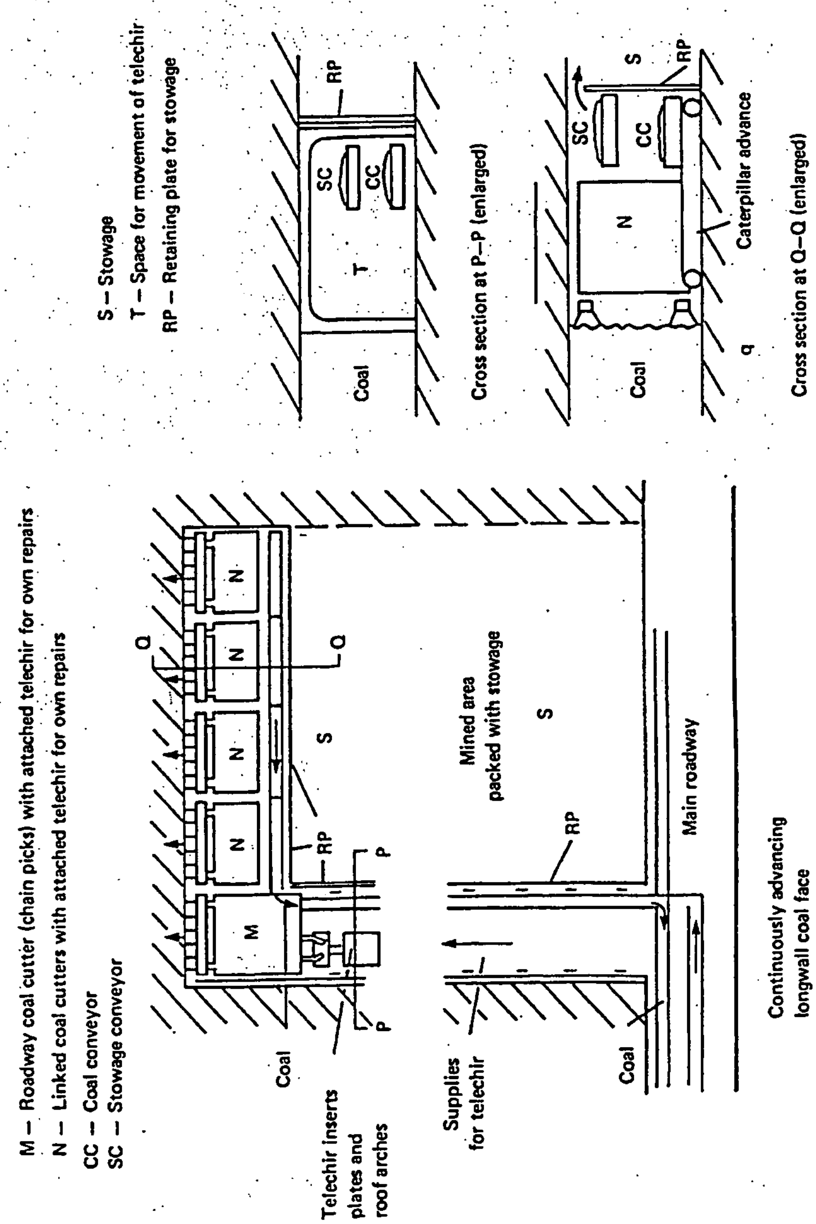


Fig. 8.28 — Possible telechiric mine layout details.

information, some type of accelerometer to give him information on the position and movement of the machine and a number of dial gauges for check out and monitoring.

Figure 8.29 shows a mine materials manipulator for working underground in thick coal seams built in the USA ('Design and application of remote manipulator systems', C. Witham, A. Fakert and A. L. Foote, *Proceedings 26th Conference on Remote Systems Technology*, 1978, p. 76). The human operator lies in it under a protecting roof with direct visual observation of the task and controls the manipulator arm by moving the handle on the control arm (Fig. 8.29(b)). Five of the six arm degrees of freedom are position–position servos (without force feedback) but the elevation is rate controlled by a lever on the control arm. Grip is controlled by a foot pedal. The arm has 2.08 m reach and 118 kg lift capacity. To reduce the danger of damage to the hydraulic lines operating the joint movements the electro hydraulic servovalves are close to the joint actuators so that only two hydraulic lines, pressure and return, are needed for the whole arm. The system is battery-operated.

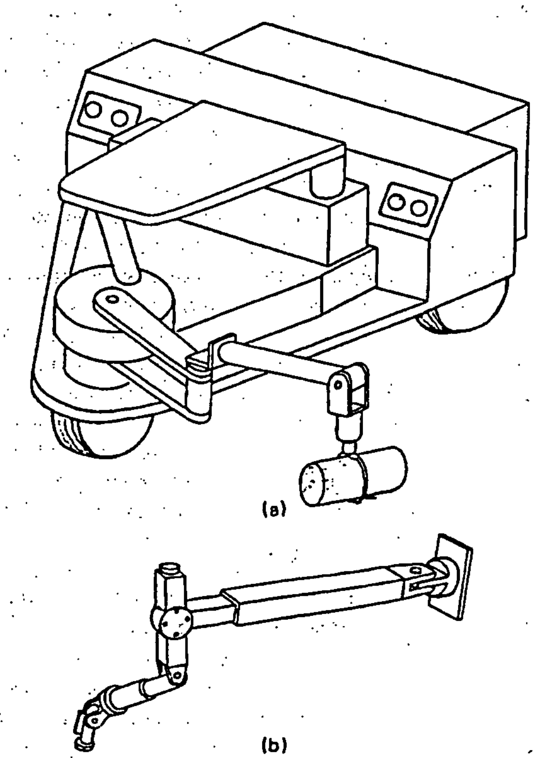


Fig. 8.29 – MBA mine materials telechir. (a) Manipulator. (B) Replica master control.

8.7 TELECHIRIC SURGERY

Thring ('Perspective', *The Blue Cross Magazine,* First Quarter, 1972, p. 27) (Fig. 8.30) has considered the possibility of telechiric surgery in which a surgeon

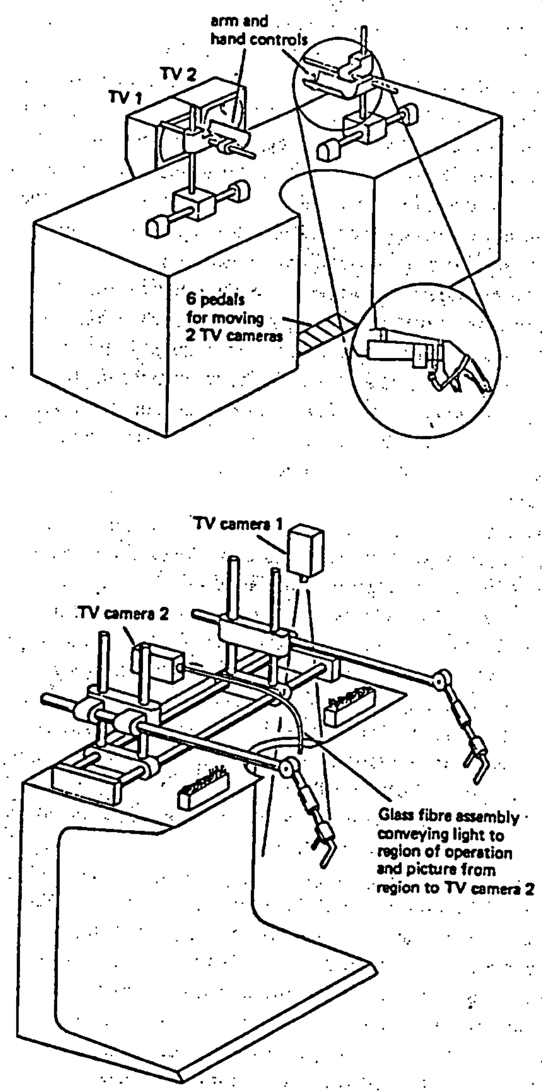


Fig. 8.30 – Surgeon's telechir.

sits at a control panel outside the sterile enclosure in which is the patient and several pairs of telechiric hands and any tools and equipment needed. The surgeon can use these pairs of hands one after another by connecting control mittens to a different terminal for each; thus he can move one pair of hands into a certain place and fix them as clamps and then work with another pair carrying different instruments. These hands of stainless steel can be stronger and thinner than his fingers or he can plug in scissors or scalpel to an arm, one set of hands can be one-tenth of the size of his own hands and when he uses these the video system would give a magnification of 10, so that he would see and feel as though his hands were the normal size but that he was operating on a patient 10 times as big. It is also possible to use multifibre optic systems for seeing round the back or inside an inaccessible part, such as the stomach with the same video screen, or he can have several video screens looking from different angles. What the surgeon sees can also be made available on other TV screens for instructional purposes or for other surgeons or nurses who can operate other hands.

One of the modern developments of surgery is sewing back severed hands or fingers in which it is necessary to sew (1) the veins and arteries which may be less then half a millimeter in diameter, (2) the main tendons to work the thumb and fingers and (3) the nerve bundles together so that sensory nerves are connected to sensory and motor nerves to motor nerves. Telechiric surgery for this type of operation could clearly be of much value in relieving the strain on the surgeons in such operations.

A. D. Alexander ('Impacts of telemation on modern society', *1st CISM-IFToMM Symposium*, Vol. 2, p. 122) has considered the possibility of surgery at great distances from the surgeon in his hospital (see Fig. 8.31). This could be life saving in the case of accidents where immediate surgical help can make all the difference or in cases at sea, down mines, or in under-developed countries. It can also be used to up-grade the quality of medical care and uses scarce medical people more effectively. In all cases two-way colour and voice TV would be essential but it would be desirable to have basic diagnostic equipment at the emergency site such as a respirometer, stethoscope, fluoroscope and image intensifier radiography. These could be operated by a para-medic on the spot or even remotely operated by telechirics. He considers also the ultimate possibiliy of remote treatment by master/slave arms.

Umetami (p. 12, *Resume of Work 1980*, Department of Physical Engineering, Tokyo Institute of Technology) has developed a micro-manipulator with tactile sensibility which can be used to grasp an object, pick it up, move it, and stab a hypodermic needle and inject fluid into it. With forceps this can handle objects of size from a few micrometres up to hundreds of microns and the force sensitivity is 10 to 100 micrograms force. A ceramic beam is used for rapid firm motion and a polymer for slow but dexterous performance. This sensitivity is obtained by the fact that the self-oscillation of a bimorphic piezoelectric beam is proportional to the contact force.

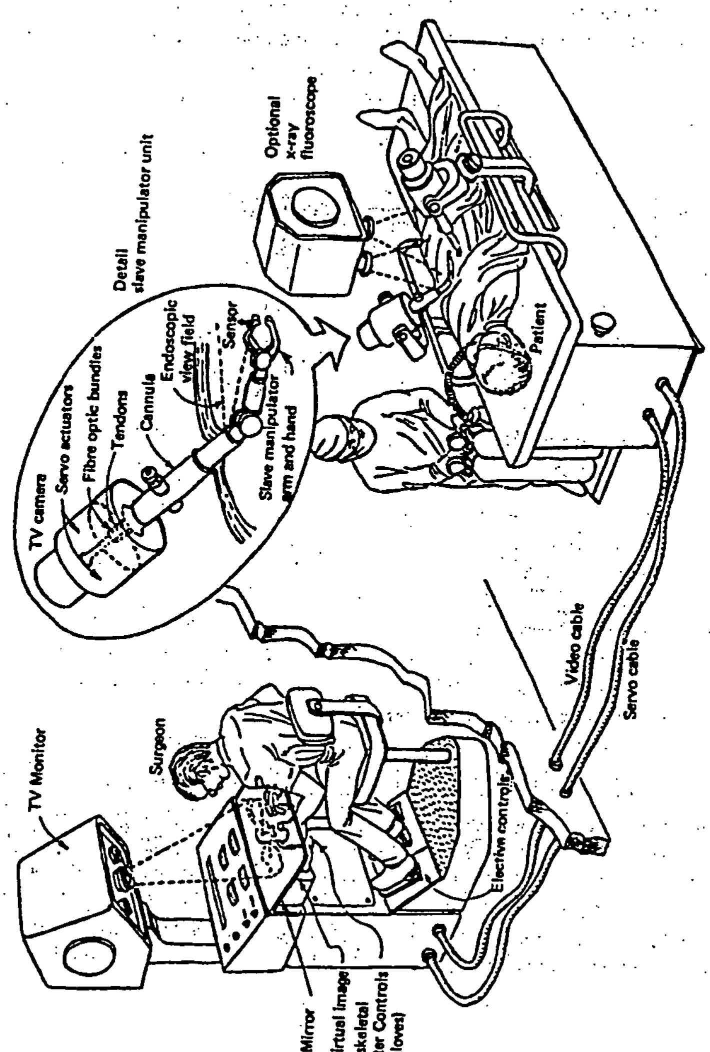


Fig. 8.31 – Remote surgery concept.

Development of a telechiric micro-manipulator which can be used without special training to give positioning resolution of μm and a frequency bandwidth of 10 Hz described at the 4th CISM-IFToMM Symposium 1981 (p. 251, 'Servo micro-manipulator "Tiny-Micro Mk. I"', K. Marsushima and H. Koyanagi). The operator holds a control shaped like a pencil connected by a control arm (see Fig. 8.32) to a fixed point as he would hold a scalpel and the slave arm

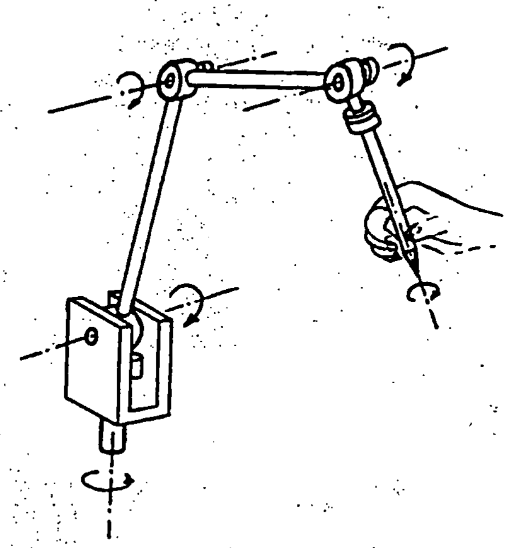


Fig. 8.32 – Control arm of a micro-telechir.

copies the movements of the control arm on a scale reduction of 150:1. All movements are R, the control arm having potentiometer position sensors full scale resolution ± 500 μm while the slave actuators are electrohydraulic with d.c. motors working a screw which pushes a diaphragm which causes a small quantity of silicon oil to flow in a tube and move a diaphragm. The stroke of the slave arm actuators is 10 mm. To reduce the offset caused by the piston torque of the actuator a non-linear compensator and tachometric feedback are used.